NUWC-NPT Technical Report 11,846
14 January 2008

Structural Analysis of the Two-Side Expandable ISO Shelter: A Floor Vibrations Mitigation Study

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NAVSEA
WARFARE CENTERS
NEWPORT

Naval Undersea Warfare Center
Newport, Rhode Island

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20080313314

PREFACE

This study was prepared under NUWC Division Newport job order C743008, principal investigator Paul V. Cavallaro (Code 70T). The research was funded by the U.S. Army Natick Soldier Center in Natick, Massachusetts, through Military Interagency Purchase Request No. MIPR 7FDAVN0885.

The technical reviewer was Andrew J. Hull (Code 8212).

Reviewed and Approved: 14 January 2008

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
14 January 2008

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

Structural Analysis of the Two-Side Expandable ISO Shelter: A Floor Vibrations Mitigation Study

5. FUNDING NUMBERS

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Undersea Warfare Center
1176 Howell Street
Newport, RI 02841-1708

8. PERFORMING ORGANIZATION REPORT NUMBER

TR 11,846

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Natick Soldier Research, Development, and Engineering Center
Natick, MA 01760-5021

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The Two-Side Expandable ISO S-786 Shelter is a tactical shelter fitted for 100-A electrical service that can be adapted for numerous civilian and military operations. Users of the surgical versions of these shelters, namely, the U.S. Army Medical Materiel Development Agency, have reported undesirable bounce or springing effects when personnel traverse the floor regions. This report documents the structural analysis of the S-786 shelter in the fully deployed position that was conducted to determine if the shelter floor vibrations could be mitigated.

14. SUBJECT TERMS

Expandable Tactical Shelter Structural Vibrations Amplitudes of Deflection and Acceleration Vibration Duration Deadweight Loading Finite Element Analysis Floor Vibrations International Standards Organization Static Loading Uniformly Distributed Load

15. NUMBER OF PAGES
27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

TABLE OF CONTENTS

Section		Page
	LIST OF TABLES	ii
	LIST OF ABBREVIATIONS AND ACRONYMS	ii
1	INTRODUCTION	1
1.1	Purpose	1
1.2	Background	1
1.3	Approach	2
2	MODEL DEVELOPMENT	3
3	STATIC LOAD CASES: BASELINE MODEL	5
3.1	1-G DEADWEIGHT LOAD CASE	5
3.2	UNIFORMLY DISTRIBUTED 1.0-PSI LOAD CASE	5
4	FREQUENCY AND MODE SHAPES	7
4.1	Baseline Model	7
4.2	Midspan-Supported Model (Upper Limiting Case)	10
4.3	Baseline Model Stiffened with Aluminum Box Beam in I-Beam Web Pocket	11
4.4	Baseline Model Stiffened with Deployable Box Beam	13
4.5	Baseline Model Stiffened with Swing-Arm Box Beams	15
4.6	Baseline Model Stiffened with Extended Subframe I-Beams	17
4.7	Baseline Model Stiffened with Increased Floor Panel Face Sheet Thickness	18
5	CONCLUSIONS	19
	REFERENCES	21

LIST OF ILLUSTRATIONS

Figure		Page
1	Two-Side Expandable ISO S-786 Shelter	1
2	Human Body Coordinate System for Identification of Vibration Directions	2
3	Baseline Model of the 100-A Two-Side Expandable ISO S-786 Shelter (floor and side wall not shown for clarity)	3
4	Aluminum Subframe Assembly	4
5	Vertical Reaction Forces of the Baseline Model at Jack Locations Caused by 1-g Deadweight Loading (Quarter-Symmetry Model)	5

LIST OF ILLUSTRATIONS (Cont'd)

Figure **Page**

6 Vertical Displacement Contours of the Baseline Model for a Uniformly Distributed 1.0-psi Floor Load (Quarter-Symmetry Model) 6
7 First Ten Symmetric Mode Shapes and Frequencies (Quarter-Symmetry Model) 7
8 Nodal Map Corresponding to Shelter Panel Center Locations 9
9 Steady-State Frequency Response Plots of Baseline Model for 0 to 100 Hz 9
10 Steady-State Resultant Displacement Behavior of the Baseline Model Plotted in Terms of Frequency Response for 0 to 20 Hz 10
11 Floor Mode at 27.31 Hz for Midspan-Supported Model 11
12 Vertical Deflection Contour Plot for Midspan-Supported Model Subjected to 1.0-psi Uniformly Distributed Floor Load 11
13 Aluminum Box Beam in I-Beam Web Pocket 12
14 Deflection and Floor Mode Shape Plots for Baseline Model Stiffened with Aluminum Box Beam (0.50-Inch-Thick Wall) in the I-Beam Web Pocket 13
15 Description and Operation of the Deployable Box Beam Stiffener 14
16 Baseline Model with Deployable Box Beam Stiffener 14
17 Deflection and Floor Mode Shape Plots for Baseline Model Stiffened with Deployable Aluminum Box (0.50-Inch-Thick Wall) 15
18 Swing-Arm Configurations 16
19 Vertical Deflection Contours for Steel 90° Swing Arm and Steel Diagonal Swing Arm Models (Wall Thickness: 0.50 Inch) 16
20 Floor Stiffening Concept Using Extended Subframe I-Beams 17
21 Vertical Deflection Contour Plot and Mode Shape for Baseline Model Stiffened with Extended Subframe I-Beams 17
22 Vertical Deflection Contour Plot and Mode Shape for Baseline Model Stiffened with Doubled Face Sheet Thicknesses of the Permanent Floor Panel 18

LIST OF TABLES

Table **Page**

1 Materials of Construction for the 100-A Two-Side Expandable ISO S-786 Shelter 3
2 Results of the Baseline Model with Deployable Box Beam Stiffeners 15
3 Performance Results and Baseline Comparisons 20

LIST OF ABBREVIATIONS AND ACRONYMS

3-D Three dimensional
A Ampere
ISO International Standards Organization

STRUCTURAL ANALYSIS OF THE TWO-SIDE EXPANDABLE ISO SHELTER: A FLOOR VIBRATIONS MITIGATION STUDY

1. INTRODUCTION

1.1 PURPOSE

The Two-Side Expandable ISO S-786 Shelter is a tactical shelter fitted for 100-A electrical service that can be adapted for numerous civilian and military operations. Users of the surgical versions of these shelters, namely, the U.S. Army Medical Materiel Development Agency (USAMMDA), have reported undesirable bounce or springing effects when personnel traverse the floor regions. More troublesome is the potential for this less-than-desirable condition of the shelter floor to adversely impact the performance of surgical procedures, exposing both patients and medical staff to unnecessary risk or harm. This report documents the structural analysis of the S-786 shelter in the fully deployed position (see figure 1) that was conducted to determine if the shelter floor vibrations could be mitigated.

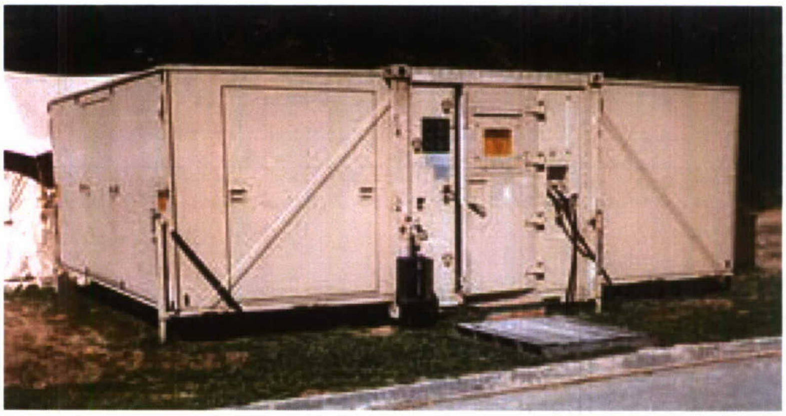


Figure 1. Two-Side Expandable ISO S-786 Shelter

1.2 BACKGROUND

Structural vibrations, particularly those occurring in floors of inhabited systems, can have a wide range of impact because perception levels of influence depend on the activities performed in that structure and will vary subjectively with the occupants and their physical positions. Key factors affecting the levels of vibration sensed by humans include amplitudes of deflection and acceleration; time duration of the vibrations (that is, transient or continuous), and the frequency content of loading.

Naeim[1] describes the human body coordinate system (shown in figure 2) that identifies the frequency ranges of maximum human sensitivity to vibration-induced accelerations in accordance with the International Standards Organization (ISO).[2, 3] Along the Z-axis (toe to head for standing positions and buttocks to head for seated positions), this range is 4 to 8 Hz. Other researchers, such as Woeste and Dolan,[4] report a slightly higher frequency range of 7 to 10 Hz for vibration sensitivity. Even higher sensitivities up to 15 Hz are reported by Dolan.[5] Naeim[1] reports this range for the X- and Y-axes as 0 to 2 Hz.

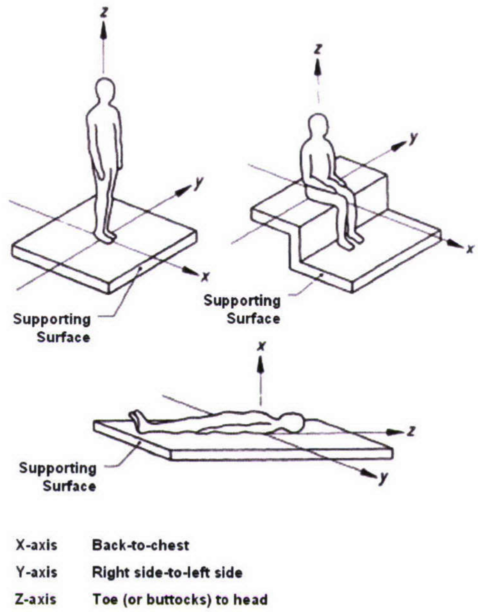


Figure 2. Human Body Coordinate System for Identification of Vibration Directions

1.3 APPROACH

The finite element method was employed using ABAQUS/Standard[6] to obtain numerical solutions of deflections, mode shapes (eigenvectors), and natural frequencies (eigenvalues). Structural modifications of the S-786 shelter were then introduced and evaluated to measure their effectiveness on increasing modal frequencies and decreasing deflections of the sandwich panel floor and subframe assembly. These modifications, which were pursued as both retrofit improvements to existing fielded shelters as well as new production shelters, were limited by two restrictions. First, the modifications could not interfere with the ISO standard dimensions for shipping containers. Second, the current floor-to-ceiling inner shelter height could not be changed. After an array of possible modifications had been developed, a down-select process was used to provide recommendations and rankings for best-fit solutions.

2. MODEL DEVELOPMENT

A baseline three-dimensional (3-D) finite element model of the current 100-A Two-Side Expandable ISO S-786 Shelter was developed (see figure 3). The aluminum/honeycomb sandwich panels (floor, side, and end walls and roof) were modeled using layered shell elements; the extrusions, corner posts, and floor subframe assembly were modeled using general shell elements; the ISO fittings were modeled using solid elements. Welds and fasteners used to provide structural connections between components were modeled using rigid link elements. Where necessary, the appropriate degrees of freedom were released to permit rotation at the hinges between panel connections. Construction material details for the various aluminum/honeycomb sandwich panels are listed in table 1. The floor subframe assembly (figure 4), miscellaneous closeouts, and other extrusions and corner posts were constructed from the aluminum alloys also listed in table 1. The ISO fittings were steel.

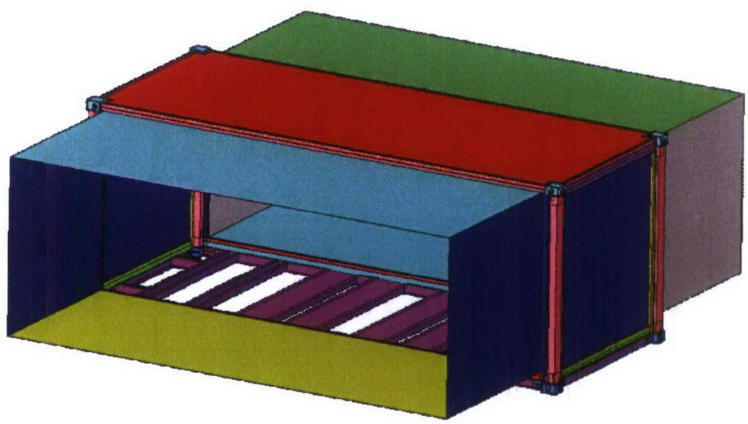


Figure 3. Baseline Model of the 100-A Two-Side Expandable ISO S-786 Shelter (floor and side wall not shown for clarity)

Table 1. Materials of Construction for the 100-A Two-Side Expandable ISO S-786 Shelter

PANEL	INNER SKIN	OUTER SKIN	CORE	THICKNESS
FLOOR	.063 6061-T6	.063 6061-T6	WRII, 3/8, 3.8lb/cf	3.0
HINGED FLOOR	.050/5052-H34	.040/5052-H34	WRII, 3/8, 3.8lb/cf	2.0
ROOF	.040/5052-H34	.050/5052-H34	WRII, 3/8, 3.8lb/cf with 1.25 in. thk 1.2-1.8 pcf polyurethane foam pressed in	2.0
HINGED ROOF	.040/5052-H34	.050/5052-H34	WRII, 3/8, 3.8lb/cf with 1.25 in. thk 1.2-1.8 pcf polyurethane foam pressed in	2.0
SIDEWALL	.040/5052-H34	.040/5052-H34	WRII, 3/8, 3.8lb/cf	2.0
HINGED SIDE	.032/5052-H34	.032/5052-H34	WRII, 3/8, 3.8lb/cf	1.5
FIXED ENDWALL	.040/5052-H34	.040/5052-H34	WRII, 3/8, 3.8lb/cf	2.5
FOLDING ENDWALL	.032/5052-H34	.032/5052-H34	WRII, 3/8, 3.8lb/cf	1.5
KNOCKOUT	.032/5052-H34	.032/5052-H34	WRII, 3/8, 3.8lb/cf	1.5
DOOR	.040/5052-H34	.040/5052-H34	WRII, 3/8, 3.8lb/cf	2.5

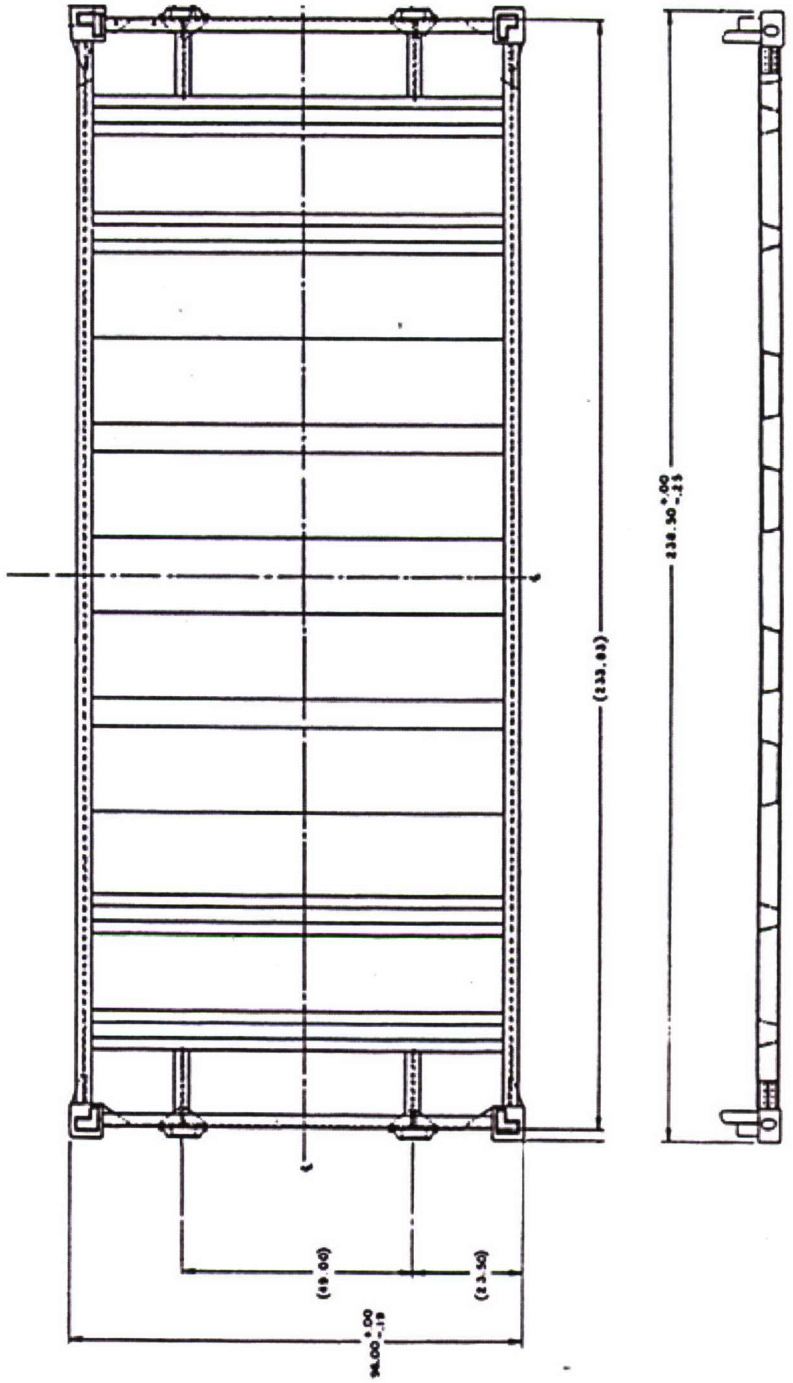


Figure 4. Aluminum Subframe Assembly

3. STATIC LOAD CASES: BASELINE MODEL

3.1 1-G DEADWEIGHT LOAD CASE

A preliminary load case was run to ensure that the full weight of the modeled shelter matched that of the actual shelter and to determine the vertical reactions at the jack support locations. This step was a necessary step to ensure that the total system mass, mass moments of inertia, and center of mass were correct prior to executing the modal analysis. A quarter-symmetry version of the full 3-D shelter was used to expedite solution time and was permissible because the shelter was symmetrical with respect to geometry, material properties, and boundary conditions. A 1-g vertical body force was applied to simulate the shelter weight. The total weight of the full shelter model was approximately 6800 lb. As shown in figure 5, vertical reaction forces at each of the four inboard and four outboard jack locations were 932.17 lb and 768.55 lb, respectively.

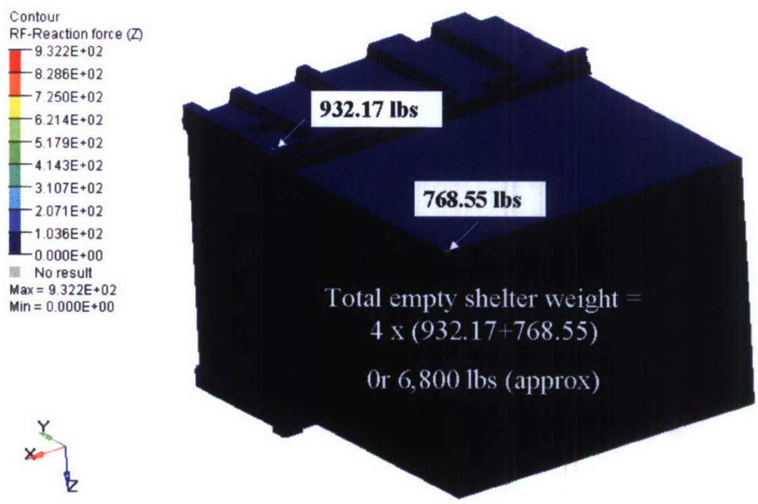


Figure 5. Vertical Reaction Forces of the Baseline Model at Jack Locations Caused by 1-g Deadweight Loading (Quarter-Symmetry Model)

3.2 UNIFORMLY DISTRIBUTED 1.0-PSI LOAD CASE

The deflection response of the floor to lateral loads in the baseline model was required for optimizing the stiffness of the floor independently of the system mass. A distributed load, therefore, was applied uniformly across the entire floor. A value of 1.0 psi was arbitrarily chosen; the resulting maximum deflection in the floor will be used for comparative purposes against those deflections obtained for the stiffened model concepts (see section 4). A plot of vertical displacement contours for the 1.0-psi distributed floor load case is shown in figure 6. The maximum vertical deflection was 1.978 inches, which occurred at the center of the floor.

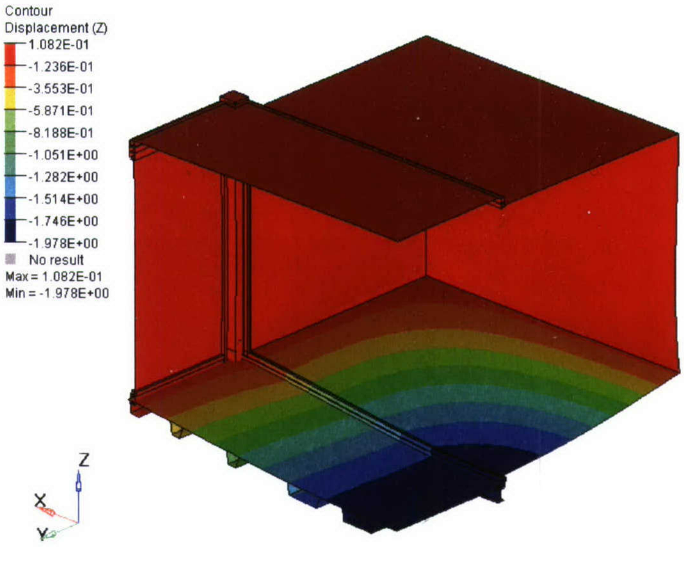


Figure 6. Vertical Displacement Contours of the Baseline Model for a Uniformly Distributed 1.0-psi Floor Load (Quarter-Symmetry Model)

4. FREQUENCY AND MODE SHAPES

4.1 BASELINE MODEL

A modal analysis was performed on the baseline model to extract the natural frequencies and mode shapes using the subspace iteration method. Although the quarter-symmetry model would permit only modes corresponding to symmetrical modes of the full shelter, for this study, the lowest mode shape corresponding to the floor region had to be established. Such a mode shape would be a half-sinusoid, thus allowing the use of a quarter-symmetry model. A cutoff frequency of 100 Hz was used. The first 10 symmetric mode shapes of the baseline shelter were plotted (see figure 7).

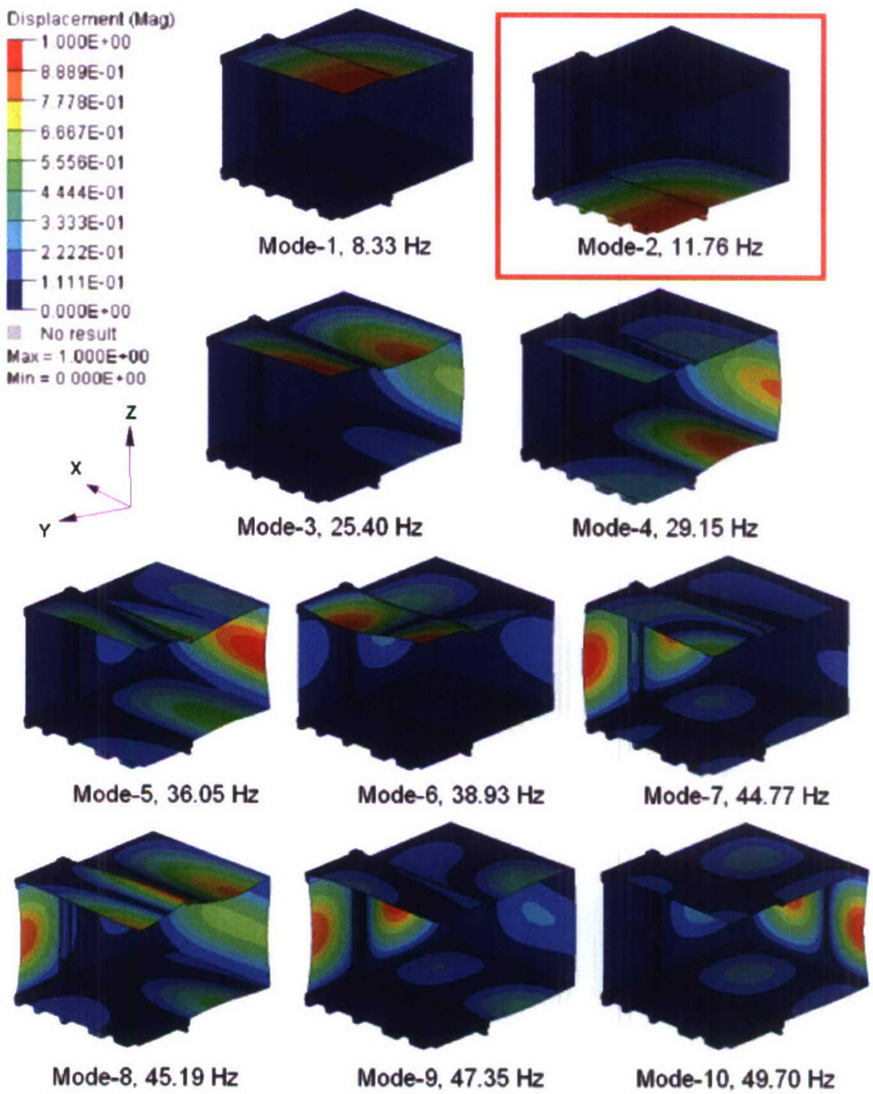


Figure 7. First Ten Symmetric Mode Shapes and Frequencies (Quarter-Symmetry Model)

As expected, the roof region, which had a natural frequency of 8.33 Hz and a half-sinusoid waveform, was first to resonate because this region was the largest unsupported section of the shelter. The second mode shape occurred in the floor region at 11.76 Hz, also with a half-sinusoid waveform and was expected to follow the roof mode prior to resonance of the side or end walls. Because the floor mode was a flexural mode, motions normal to the floor would be excited. This frequency, which approaches the upper sensitivity limit for individuals along the Z-axis of figure 2, corresponds to the standing and seated positions. Furthermore, this frequency is the frequency of interest and the suspected source of annoyance.

Solutions to the floor springing effect should generally be based on design modifications that increase the floor natural frequency f and bending stiffness EI in which E is the elastic modulus and I is the second area moment of inertia. For ribs within a stiffened panel assembly, the fundamental natural frequency is given by the following equation:

$$f = 1.57 * \sqrt{\frac{386EI}{mgL^3}}, \tag{1}$$

where m is the total supported mass, g is the acceleration due to gravity, L is the supported span length.

Equation (1) identifies the parameters influencing the fundamental frequency of the floor. The product EI in equation (1) represents the combined value of bending stiffness for the sandwich floor and subframe assembly. One approach to increasing f is to reduce the combined mass of these components with no loss in EI. However, such an approach was not considered practical because these components are relatively lightweight and must maintain sufficient structural integrity (strength, stiffness, and toughness) to survive the operational and transitory environmental loads associated with portable systems. Rather, the modifications considered in the current study attempted to effect increases in f at the expense of additional mass with consideration given to practicality, manufacturing, weight, operation, ISO dimensional compliance, and cost.

A frequency response analysis of the baseline model was performed to obtain its steady-state dynamic behavior when the model was subjected to a distributed load case. A 1-g gravitational load was applied along the global X- , Y- , and Z-axes simultaneously with an excitation frequency range of 0 to 100 Hz. Steady-state displacements were obtained at the central nodes for each panel surface in accordance with the nodal map of figure 8. The resulting frequency response plots, which are shown in figure 9, captured the modes and excitation directions observed in figure 7. Figure 10 shows the steady-state resultant displacements plotted in terms of frequency response over 0 to 20 Hz.

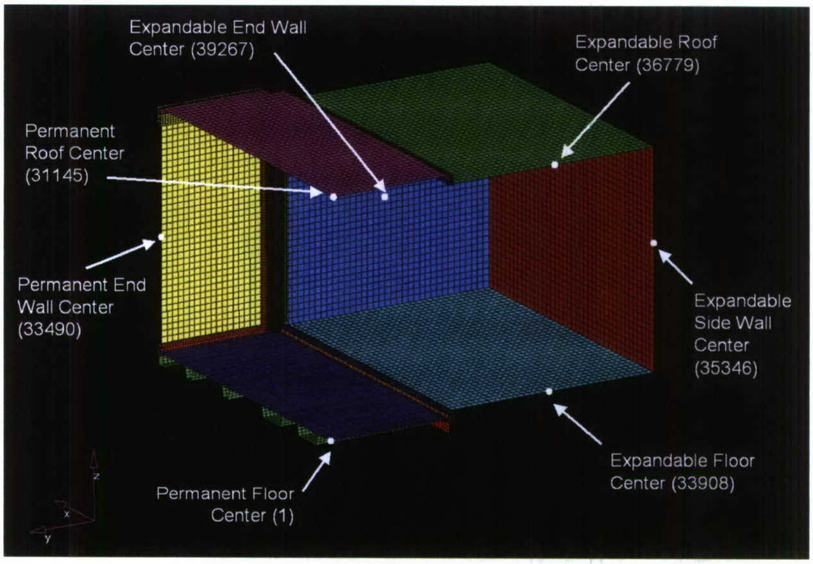


Figure 8. Nodal Map Corresponding to Shelter Panel Center Locations

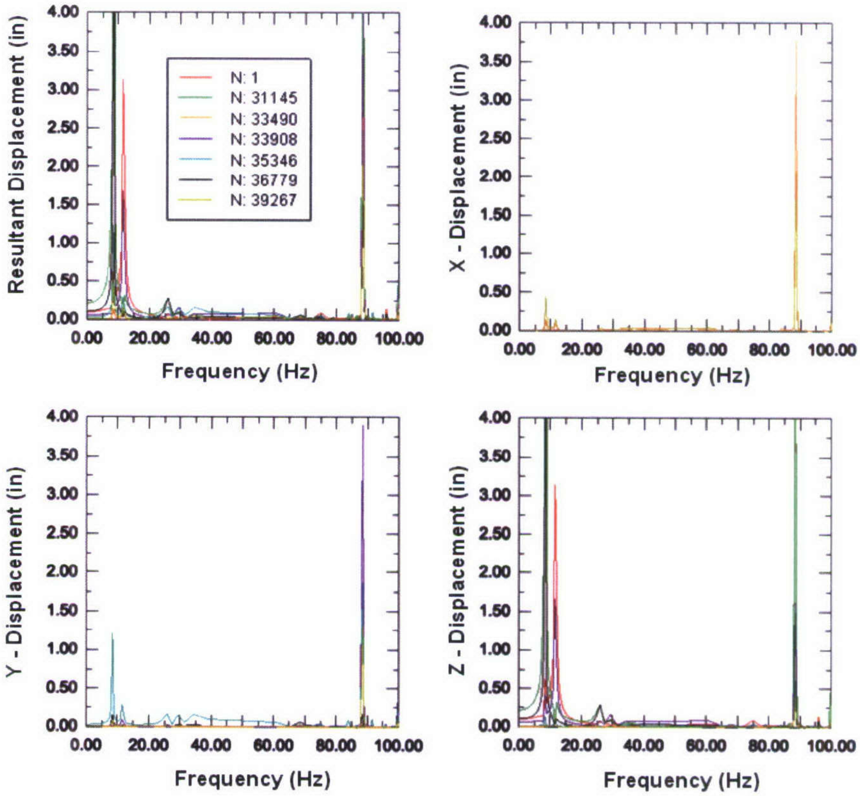


Figure 9. Steady-State Frequency Response Plots of Baseline Model for 0 to 100 Hz

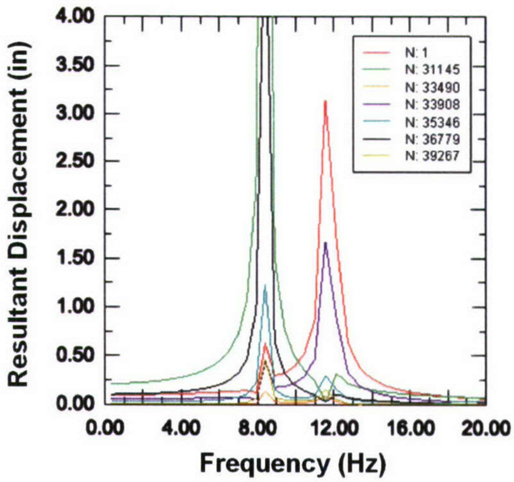


Figure 10. Steady-State Resultant Displacement Behavior of the Baseline Model Plotted in Terms of Frequency Response for 0 to 20 Hz

4.2 MIDSPAN-SUPPORTED MODEL (UPPER LIMITING CASE)

A midspan-supported version of the baseline model was modeled to define realistic limits of structural responses. Of all the models considered in this study, the floor region frequency of the midspan-supported model was expected to be a relative maximum; likewise, the maximum floor deflection for this model, when subjected to the 1.0-psi uniformly distributed floor load, was expected to be a relative minimum. Displacement boundary conditions for this model were identical to previous models except for the additional jack points to support the shelter at the midspan of the I-beams within the floor subframe assembly (see figure 11). These additional jack points, however, would not only increase in operational setup time, but also would require soldiers to maneuver underneath the deployed shelter to make the appropriate height adjustments to maintain these additional jack points in the presence of soil settling. Field adjustments may be considered undesirable from the operational perspective, thus ranking this stiffening option less attractive. Several stiffening alternatives that avoided the need for field adjustments were considered and subsequently evaluated. (At this time, an automated self-leveling jack system is under development by the U.S. Army Soldier Systems Center. This system would alleviate the problem of manual adjustments for standard jacks, thus making the midspan jack method of stiffening most attractive.)

The natural frequency of the floor region for the midspan supported model was 27.31 Hz, which represents a frequency shift (increase) 2.4 times higher than that of the baseline model. The corresponding mode shape plot is shown in figure 11. Note that the variation of resultant displacement across the permanent floor section is minimal. This suggests that the permanent floor section is sufficiently stiff in bending along the lateral direction of the shelter while appreciable curvature occurs laterally in the expandable floor regions. The peak deflection for the 1.0 psi uniformly distributed floor load case was 0.542 inch occurring at the center of the expandable floor region. A contour plot of vertical displacement is shown in figure 12. Both the floor frequency and 1.0-psi load case deflection results of the midspan-supported model served as limits for comparative purposes to those obtained in the alternatively stiffened models.

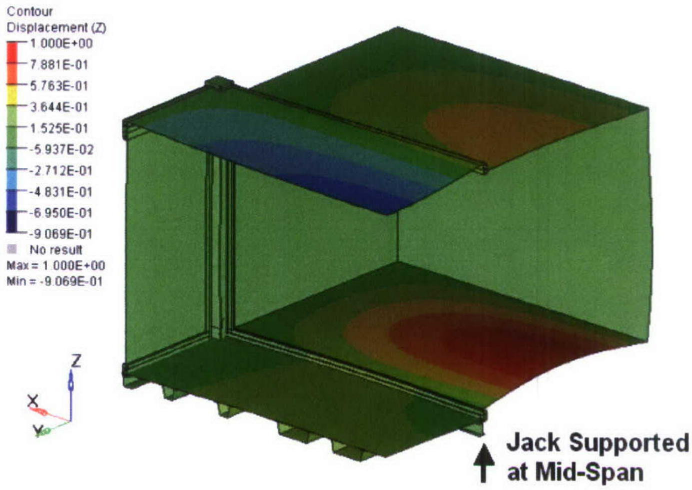


Figure 11. Floor Mode at 27.31 Hz for Midspan-Supported Model

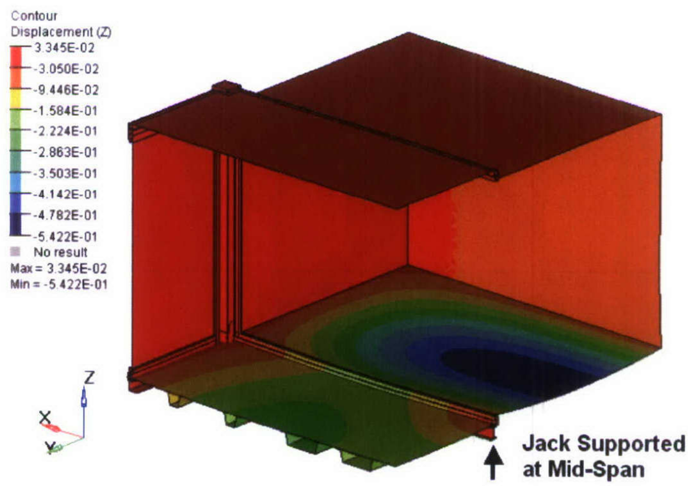


Figure 12. Vertical Deflection Contour Plot for Midspan-Supported Model Subjected to 1.0-psi Uniformly Distributed Floor Load

4.3 BASELINE MODEL STIFFENED WITH ALUMINUM BOX BEAM IN I-BEAM WEB POCKET

A stiffening option in which box beams were secured within the outboard web pockets of the longitudinal I-beams in the floor subframe assembly was considered. If successful, this option would be easy to accommodate in both retrofit operations and in new shelter productions. This option (see figure 13) was evaluated for aluminum box beams of two different wall thicknesses, namely 0.25 inch and 0.50 inch. The box beam width was intentionally restricted to prevent projecting beyond the width of the I-beam, ensuring continued compliance with the required ISO container envelope dimensions. The additional weight per box beam realized by this concept was 60.76 lb for the 0.25-inch-thick wall and 121.49 lb for the 0.50-inch-thick wall.

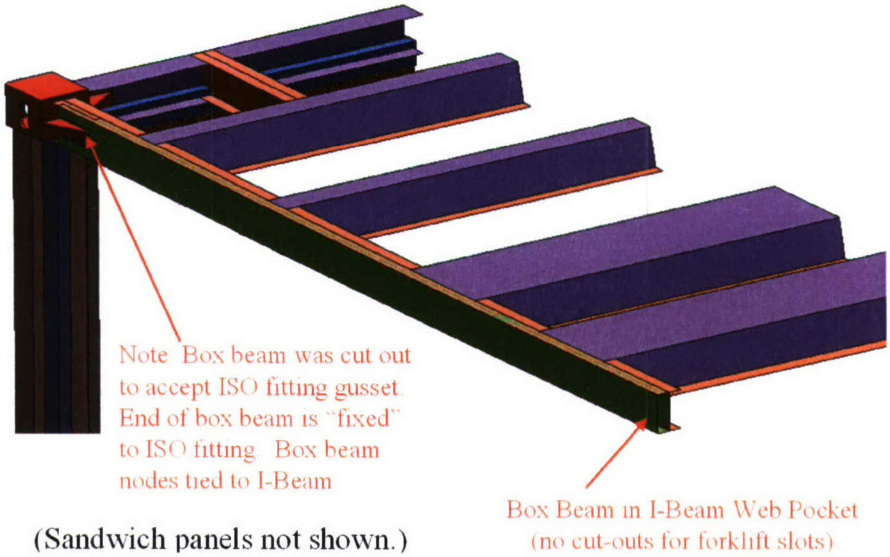


Figure 13. Aluminum Box Beam in I-Beam Web Pocket

The stiffness benefit provided by this concept to the I-beam of the subframe assembly can be readily computed in terms of the area moment of inertia using the parallel axis theorem as shown in equation (2).

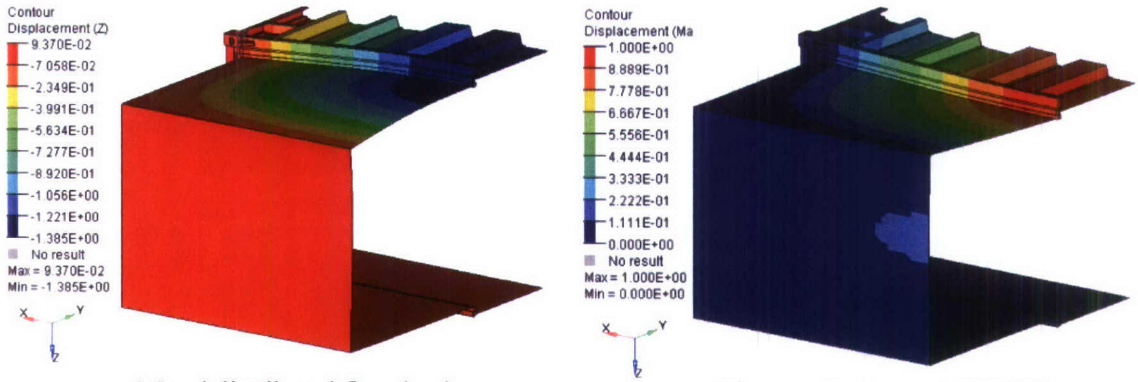
$$I_{assembly} = I_{I-beam} + I_{boxbeam} + A_{boxbeam} d_{offset}^2, \tag{2}$$

where $A_{boxbeam}$ is the cross-sectional area of the box beam and d_{offset} is the distance between centroids of the I-beam and box beam.

When the floor of the reinforced aluminum box beam models was subjected to the 1.0-psi distributed floor load, the maximum floor deflection was 1.54 inches for the 0.25-inch-thick wall model and 1.39 inches for the 0.50-inch-thick model. Natural frequencies of the floor region were 12.79 Hz and 13.09 Hz for the 0.25- and 0.50-inch-thick wall models, respectively.

Deflections for the 1.0-psi load case and floor mode shape are shown in the contour plots in figure 14 for the aluminum box beam model with wall thickness of 0.50 inch. In comparison to the baseline model, the current stiffening concept provided minimal shifts in the floor region natural frequencies. This result is explained further in accordance with equation (2) and realizing that the centroid location of the combined floor sandwich panel and floor subassembly lies vertically in proximity to the I-beam centroid. It becomes apparent that the box beam stiffening effect does not utilize the $A_{boxbeam}\, d_{offset}^2$ term because d_{offset} is nearly zero. Increasing the wall thickness of the box beam beyond what is even practical will therefore not provide any considerable increase in $I_{assembly}$. Furthermore, for any appreciable increase in $I_{assembly}$, a significant weight penalty would result.

Additional models were evaluated using steel box beams with 0.25-inch and 0.50-inch wall thicknesses. The results of these models are reported in section 5.



1.0-psi distributed floor load

Floor mode shape at 13.09 Hz

Figure 14. Deflection and Floor Mode Shape Plots for Baseline Model Stiffened with Aluminum Box Beam (0.50-Inch-Thick Wall) in the I-Beam Web Pocket

4.4 BASELINE MODEL STIFFENED WITH DEPLOYABLE BOX BEAM

This stiffening concept, as shown in figures 15 and 16, incorporates articulating box beams that, once deployed, utilize the benefit of the $A_{boxbeam}\, d_{offset}^{\,2}$ term in equation (2). The box beam is hinged and operated as shown in figure 15, so that when it is deployed, the $A_{boxbeam}\, d_{offset}^{\,2}$ term becomes significant. The deployable box beams are designed to be stowed within the I-beam's outboard web pockets with zero interference to the shelter when it is not in operational mode. No change to the existing ISO S-786 shelter envelope (height, length, and width) occurs when stowed (hinge point can be moved to the right from that as shown in figure 15). During operational mode, the box beams are rotated along the hinge axis and locked into position beneath the I-beam prior to expanding the side walls. Unlike the midspan supported model described in section 4.2, this concept does not require field adjustments to correct for soil compaction. Prior to shelter transit, the process is reversed. The expandable walls are collapsed, and the box beam stiffeners are unlocked and rotated back into the I-beam web pockets for stowage. If forklift access remains a requirement, slots can be machined in the box beams—without adversely affecting the bending stiffness of the box beams. The following features are additional benefits of the deployable box beam concept:

1. Eccentricities between the I-beam and deployable box beam are minimized. Note that the width of the deployed box beam matches the width of the I-beam, resulting in their centers being vertically aligned.

2. The area moment of inertia for the combined deployable box beam/I-beam assembly can be increased by 100% or more beyond that of the I-beam alone at minimal weight and cost.

3. The most efficient method of maximizing stiffness while minimizing added stiffener weight is through utilization of the $A_{boxbeam}\, d_{offset}^{\,2}$ term.

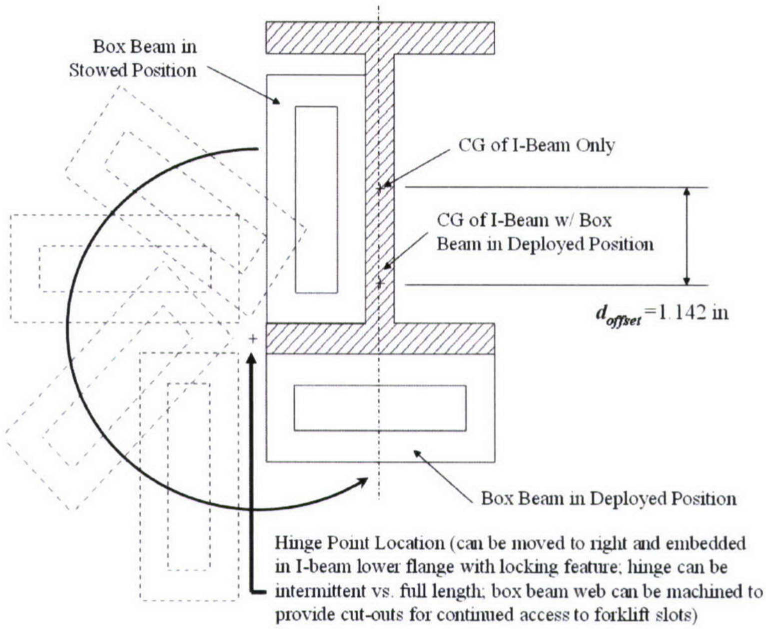


Figure 15. Description and Operation of the Deployable Box Beam Stiffener

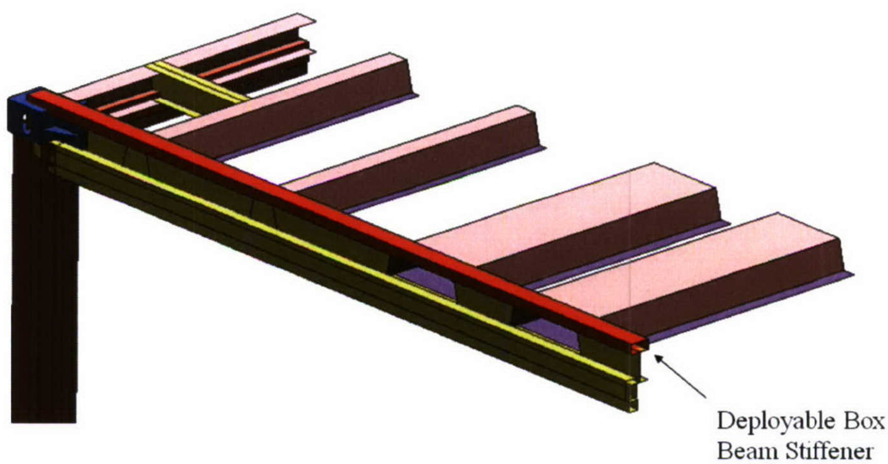


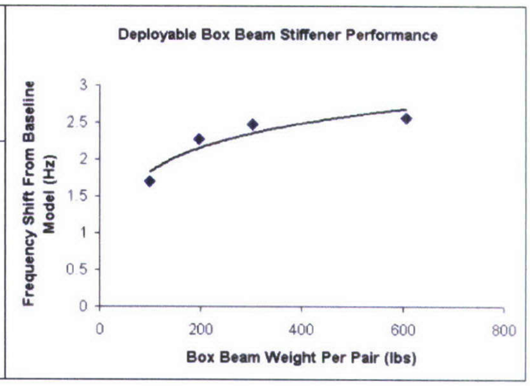
Figure 16. Baseline Model with Deployable Box Beam Stiffener

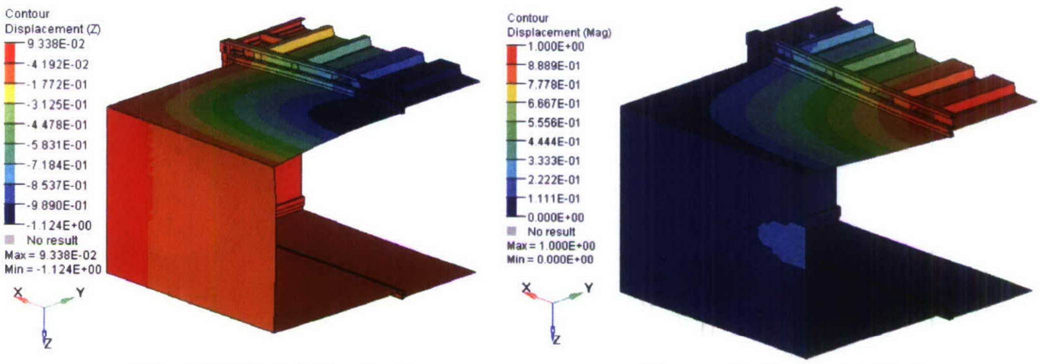
The baseline model was modified to accept deployable box beams having an outer width of 3 inches and an outer height of 1.5 inches. (Note that these dimensions are in reference to the deployed configuration.) The model was run for two different box beam wall thicknesses and two different materials as shown in table 2. Results of the baseline shelter model incorporating deployed 0.50-inch-thick wall aluminum box beam stiffeners indicated that the peak deflection of the floor region for the 1.0-psi uniformly distributed load was 1.12 inches. The fundamental frequency of the floor region was 14.04 Hz, representing a frequency shift of 2.27 Hz over the baseline shelter. The corresponding deflection and floor region mode shape are shown in figure 17. The added weight to the shelter for a pair of 0.50-inch wall aluminum deployable box beams was 198 lb.

Table 2. Results of the Baseline Model with Deployable Box Beam Stiffeners

Material	Wall Thickness (in)	Box Beam Weight Per Pair* (lbs)	Floor Frequency (Hz)	Frequency Shift (From Baseline) (Hz)	Maximum Floor Deflection From 1.0 psi Load (in)	Ratio of Frequency Shift to Box Beam Pair Weight (Hz/lb)
Aluminum	0.25	99	13.46	1.70	1.24	0.017
Aluminum	0.5	197.99	14.04	2.28	1.11	0.012
Steel	0.25	303.09	14.23	2.47	1.06	0.008
Steel	0.5	606.21	14.32	2.56	0.98	0.004

*Weight is based on 2 deployable box beams (i.e., one for roadside I-beam and one for curbside I-beam)





1.0-psi distributed floor load

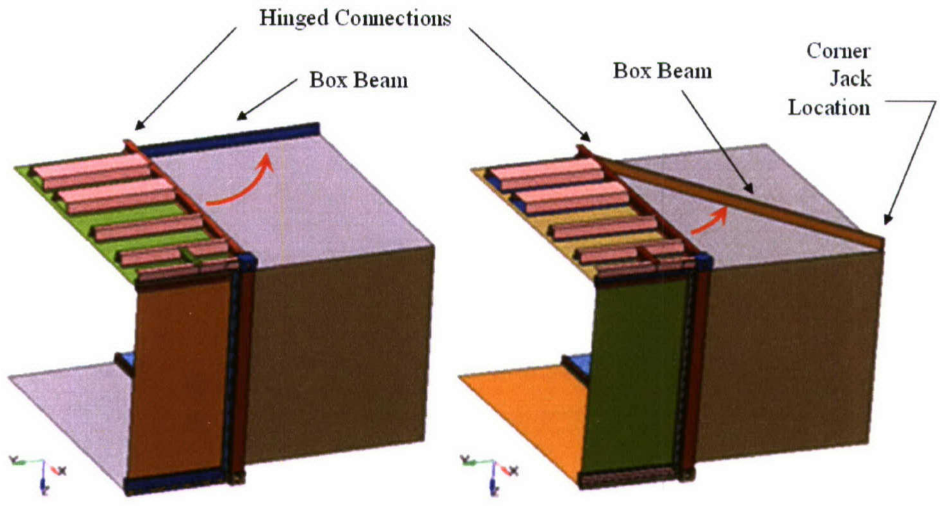
Floor mode shape at 14.04 Hz

Figure 17. Deflection and Floor Mode Shape Plots for Baseline Model Stiffened with Deployable Aluminum Box (0.50-Inch-Thick Wall)

4.5 BASELINE MODEL STIFFENED WITH SWING-ARM BOX BEAMS

The next considered option was the deployable swing arm stiffener, in which box beams that are initially stowed within the outboard web pockets of the present I-beams, are rotated into operational position and secured underneath the expandable floor sections. This concept (see figure 18) provides lateral reinforcement to the expandable floor sections. The inboard ends of the swing arm stiffeners are hinge-connected at the midspans of the present I-beams.

Two swing-arm configurations were evaluated. The first configuration uses two swing arms that rotate 90° to a securing position along the outboard edge of the expandable floors. The second configuration uses four swing arms that rotate out toward the outboard corner jacks of the expandable floors. The latter configuration is referred to as "a diagonal swing-arm arrangement." These swing arms must be telescopic to bridge the span from the midspan of the I-beams to the corner jacks. The effectiveness of the swing-arm stiffening methods is limited by the I-beam pocket width of 1.5 inches. Because the swing-arm box beams must be stowed within the current I-beam web pockets to stay in compliance with the allowable ISO dimensions, the maximum outer width and height dimensions of the swing-arm box beams are 1.42 inches and 4.18 inches, respectively.



90° Swing Arm Diagonal Swing Arm

Figure 18. Swing-Arm Configurations

Results of the baseline model stiffened with the steel-swing arm, whose wall thickness is 0.50 inch, were shown to be partly successful. Recalling the baseline floor deflection of 1.98 inches for the 1.0-psi distributed load case, floor deflections were reduced to 1.859 inches (6.1%) and 1.511 inches (23.7%) for the 90° swing arm and diagonal swing arm models, respectively (see figure 19). Floor frequencies, however, decreased from the baseline model of 11.76 Hz to 11.57 Hz (– 1.6%) for the 90° swing arm and 11.41 Hz (– 2.9%) for the diagonal swing-arm models. Additional results for the 0.25-inch-thick wall and 0.50-inch wall aluminum swing arm reinforced models are shown in the summary section. Referring to equation (1), the swing arm stiffening methods did not satisfy the balance between the combined ***EI*** and added mass.

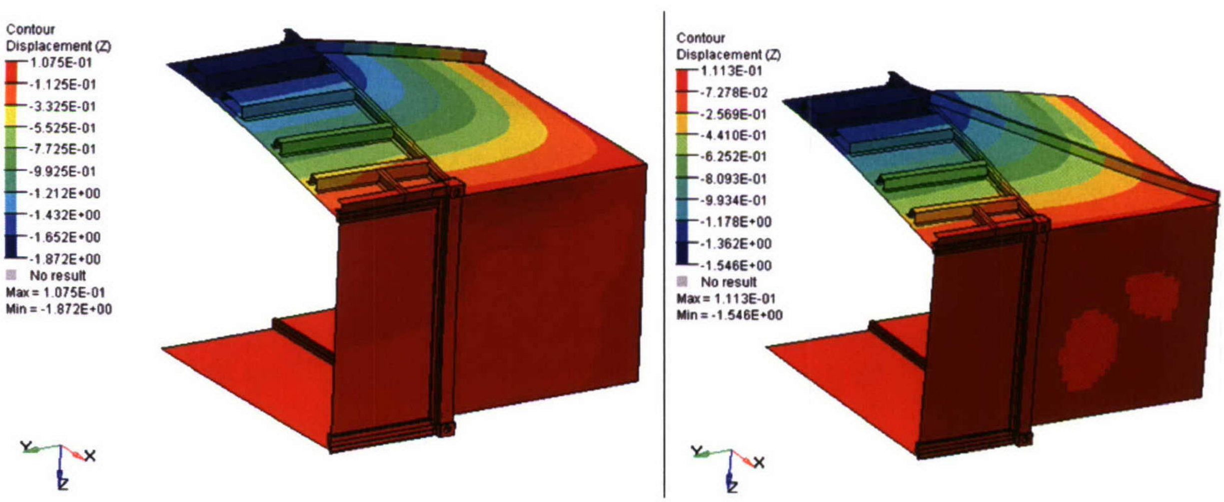
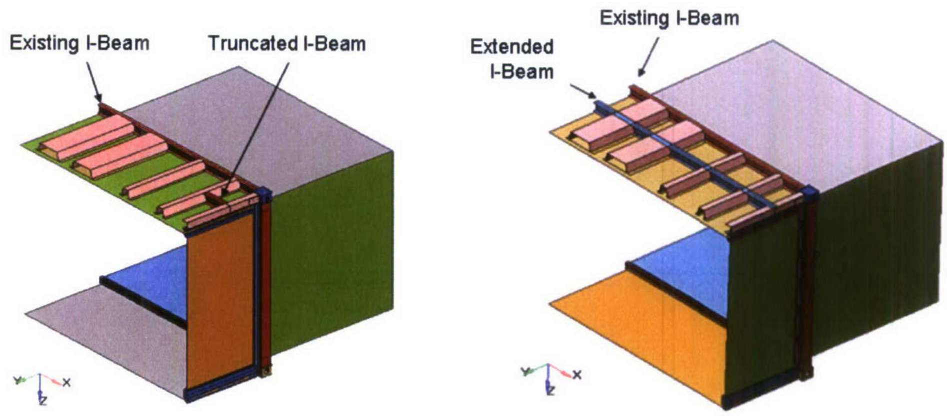


Figure 19. Vertical Deflection Contours for the Steel 90° Swing Arm and Steel Diagonal Swing Arm Models (Wall Thickness: 0.50 Inch)

4.6 BASELINE MODEL STIFFENED WITH EXTENDED SUBFRAME I-BEAMS

The next reinforcement method was considered for new ISO shelter constructions and was developed by extending the current truncated I-beams within the subframe assembly to the full length of the assembly as shown in figure 20. This method would double the number of I-beams but would likely have only a marginal reinforcement effect in contrast to the previously evaluated box-beam-in-I-beam-web-pocket method. The reason for only a marginal improvement arises from the fact that the I-beam flanges are only 0.16 inch thick.

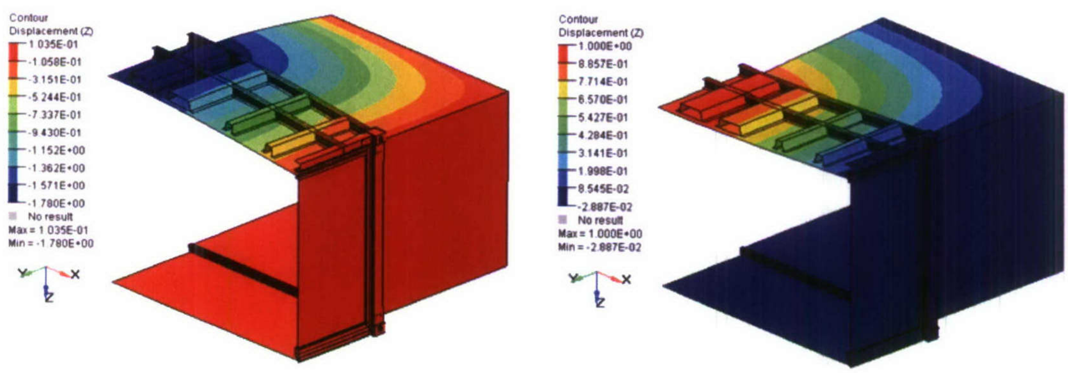


Baseline Construction

Extended I-beam

Figure 20. Floor Stiffening Concept Using Extended Subframe I-Beams

As expected, the extended I-beams concept was minimally successful, with only a 10% reduction in floor deflection (1.78 inches) and a 3.7% increase in floor frequency (12.20 Hz) compared to the baseline model (see figure 21). This concept could be modified to achieve greater performance by increasing the flange thicknesses of each I-beam and/or using steel rather than aluminum. A material substitution, however, would result in manufacturing issues for the various welding operations performed on the subframe assembly.



1.0-psi distributed load

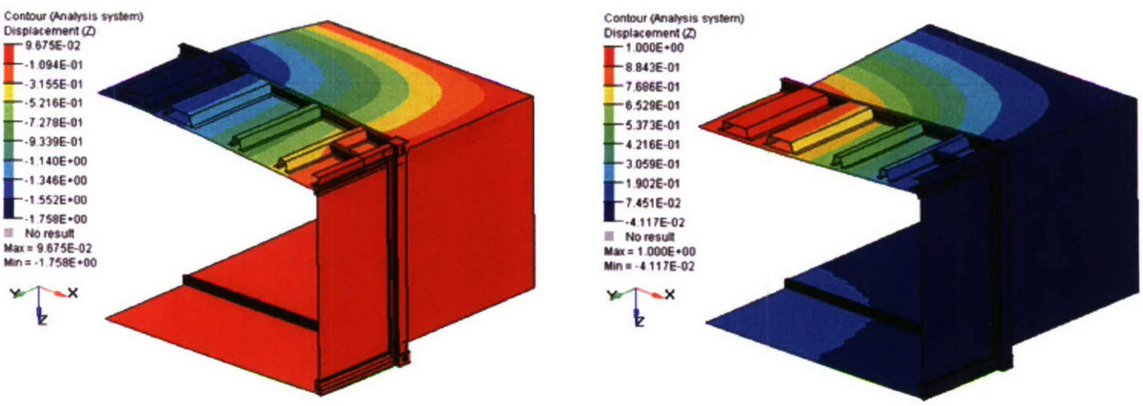
Floor mode at 12.20 Hz

Figure 21. Vertical Deflection Contour Plot and Mode Shape for Baseline Model Stiffened with Extended Subframe I-Beams

4.7 BASELINE MODEL STIFFENED WITH INCREASED FLOOR PANEL FACE SHEET THICKNESS

The effect of doubling the face sheet thicknesses of the floor sandwich panels was investigated as a potential stiffening method for new shelter constructions. This concept was evaluated for two separate models, namely one that doubled the face sheet thicknesses of the permanent floor sandwich panel and one that doubled the face sheet thickness of the expandable floor sandwich panels. In both models, the original sandwich panel thicknesses remained unchanged, which was achieved by reducing the honeycomb core thickness to accommodate the increases in face sheet thicknesses (Cavallaro and Jee's article[7] about the design of a lightweight, rigid-wall shelter thoroughly discusses the relevant mechanics of materials for similarly constructed sandwich panels).

Results showed that, for doubling the face sheet thickness of the permanent floor region, the deflection from the 1.0-psi load case was 1.76 inches, a decrease from the baseline model of 11.1% (see figure 22). The floor frequency, however, was 10.34 Hz, which represented a decrease of 8.3% from the baseline model. For the model with doubled face sheet thicknesses of the expandable floor panels, the 1.0-psi load case deflection was 1.70 inches, a decrease from the baseline model of 14.1%. The floor frequency was 11.69 Hz, a decrease from the baseline model of 0.6%. This stiffening method was unsuccessful and did not satisfy the balance between mass and combined stiffness as described by equation (1) for the face sheet thicknesses considered.



1.0-psi distributed load

Floor mode at 10.34 Hz

Figure 22. Vertical Deflection Contour Plot and Mode Shape for Baseline Model Stiffened with Doubled Face Sheet Thicknesses of the Permanent Floor Panel

5. CONCLUSIONS

The finite element method was particular useful in establishing structural and modal behaviors of the Two-Side Expandable ISO S-786 Shelter. Characterization of panel deflections, mode shapes, and natural frequencies enabled the evaluation of various conceptual stiffening methods to mitigate annoying floor vibrations presently confronting users of the surgical version of the S-786 shelter. Comparisons were made between the natural frequencies computed by the models to the sensitivity ranges reported for humans. While the ranges of sensitivity are subjective, it was concluded that, for the current (baseline) shelter, the natural frequency of the floor (11.76 Hz) is within the sensitivity range for humans.

Performance results, including maximum deflections for the 1.0-psi uniformly distributed floor load case and frequency shifts from the modal analyses, were tabulated so that efficiencies could be computed and normalized by the added mass of the stiffening concept (see table 3).

The swing-arm concepts, within the constraint of allowable box-beam widths, and the increased face-sheet thickness method clearly do not contribute effectively because of their inability to provide sufficient increases in combined floor stiffness that compensate for the added masses in accordance with equation (1). The beam-in-web-pocket method of stiffening, which is also limited by the width restriction of the available I-beam web pocket, provides frequency shifts of up to only 1.34 Hz. The extended I-beams concept was shown to provide a frequency shift less than 0.5 Hz, resulting directly from the slenderness of the flanges.

Two stiffening concepts recommended for further consideration are the deployable box-beams and the midspan jacks. The deployable box beam method capitalizes on its ability to effectively increase the depth of the subframe assembly during operation and can be retrieved so it does not interfere with the shelter during mobile transit. This concept increases setup time and includes a modest weight penalty, but it does not require field adjustments for changing soil conditions. The frequency shifts obtained for the deployable box-beam wall thicknesses and materials considered may not be sufficient, however, to overcome the range of subjective human sensitivity levels to vibration. Modal testing is, therefore, recommended for this option along with user feedback. The midspan jack method reduces floor deflections by 72% of the baseline, achieves a frequency shift of 15.54 Hz (a natural frequency of 27.31 Hz); it is, therefore, ranked as the primary solution to the floor vibration problem. If the midspan jack is configured as a manual system, field adjustments will be required to compensate for any changes in soil compaction. The midspan jack concept increases setup time and weight and requires stowage space. This concept can be implemented as retrofits to current fielded shelters and can be integrated in new production shelters.

Table 3. Performance Results and Baseline Comparisons

Model Description	Weight Per Stiffener (lb)	# Stiffeners Per Shelter	Total Stiffener Weight Per Shelter [1] (lb)	Max Floor Deflection (in)	Floor Frequency (Hz)	Deflection Ratio to Baseline	Frequency Shift (Hz)	Efficiency [2]	Effiency/ Total Weight (lb^{-1})
Baseline	N/A	N/A	N/A	1.98	11.76	1.00	N/A	**N/A**	N/A
Baseline with Mid-Span Jack	N/A	N/A	N/A	0.54	27.31	0.27	15.54	**56.70**	N/A
¼" Wall Alum. Box Beam In I-Beam Web Pocket	60.76	2	121.52	1.54	12.79	0.78	1.03	**1.32**	0.0109
½" Wall Alum. Box Beam In I-Beam Web Pocket	121.49	2	242.97	1.39	13.09	0.70	1.33	**1.90**	0.0078
¼" Wall Steel Box Beam In I-Beam Web Pocket	186.02	2	372.03	1.30	13.10	0.66	1.34	**2.03**	0.0055
½" Wall Steel Box Beam In I-Beam Web Pocket	372.11	2	744.21	1.14	12.97	0.58	1.21	**2.09**	0.0028
Extended Alum. I-Beams in Floor Sub Frame	330.22	2	660.44	1.78	12.20	0.90	0.44	**0.49**	0.0007
Increased Thickness of Alum. Skins in Permanent Floor [3]	N/A	N/A	274.11	1.76	10.34	0.89	-1.42	**-1.60**	-0.0058
Increased Thickness of Alum. Skins in Expanded Floor [4]	N/A	N/A	319.07	1.70	11.69	0.86	-0.07	**-0.08**	-0.0003
¼" Wall Alum. Box Beam 90° Swing-Arm	23.18	2	46.36	2.00	11.65	1.01	-0.11	**-0.11**	-0.0024
½" Wall Steel Box Beam 90° Swing-Arm	142.12	2	284.24	1.86	11.57	0.94	-0.20	**-0.21**	-0.0007
¼" Wall Alum. Box Beam Diagonal Swing-Arm	38.95	4	155.79	1.72	11.72	0.87	-0.04	**-0.05**	-0.0003
½" Wall Alum. Box Beam Diagonal Swing-Arm	77.86	4	311.44	1.66	11.73	0.84	-0.03	**-0.04**	-0.0001
¼" Wall Steel Box Beam Diagonal Swing-Arm	119.21	4	476.82	1.61	11.66	0.82	-0.11	**-0.13**	-0.0003
½" Wall Steel Box Beam Diagonal Swing-Arm	238.41	4	953.65	1.51	11.41	0.76	-0.35	**-0.46**	-0.0005
¼" Wall Alum. Deployable Box Beam	49.50	2	99.00	1.26	13.46	0.64	1.70	**2.67**	0.0269
½" Wall Alum. Deployable Box Beam	99.00	2	197.99	1.12	14.04	0.57	2.27	4.00	0.0202
¼" Wall Steel Deployable Box Beam	151.55	2	303.09	1.07	14.23	0.54	2.47	**4.58**	0.0151
½" Wall Steel Deployable Box Beam	303.11	2	606.21	0.98	14.32	0.49	2.56	**5.19**	0.0086

[1] - Total stiffener weight is the weight sum of all repeated components for a given stiffening method (exludes weight of additional jacks).

[2] - Efficiency defined as the ratio of frequency shift to baseline deflection ratio.

[3] - Aluminum skins of the this floor section were increased from 0.063" to 0.125" thick with the core thickness reduced to maintain the original total floor panel thickness.

[4] - Aluminum skins of the this floor section were increased from 0.05" for the inner skin and 0.04 for the outer skin to 0.10" for the inner skin and 0.09" for the outer skin with the core thickness reduced to maintain the original total floor panel thickness.

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